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Towards Intelligent Machine-to-Machine Communications in Smart Grid

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***Abstract*—The Advanced Metering Infrastructure (AMI) of Smart Grid (SG) presents the biggest growth potential in the Machine-to-Machine (M2M) market today. Spurred by advances in the M2M technologies in recent time, the SG smart meters are expected not to require human intervention in characterizing power requirements and energy distribution. However, there are many challenges in the design of the SG communications network whereby the electrical appliances and smart meters are able to exchange information pertaining to varying power requirements. Furthermore, different types of M2M gateways are required at different points (e.g., at home, in the building, at the neighborhood, and so forth) of the SG communication network. This article surveys a number of existing communication technologies that can be adopted for M2M communication in SG. Among those, the most reliable technology to facilitate M2M communication in the SG home area network is pointed out and its shortcoming is also noted. Furthermore, a possible solution to deal with the shortcoming to improve the SG communications scalability is also presented.**

***Index Terms*—Smart Grid, Machine-to-Machine (M2M) communication.**

I. Introduction

THIS decade is widely predicted to see the rise of Machine-to-Machine (M2M) communications over wired and wireless links. For instance, statistics suggest that, by 2014, there would be 1.5 billion wirelessly connected devices that are not mobile phones and do not require any human intervention. This will lead to an unprecendented increase in the data traffic involving machines communicating with other machines without human interaction. Various applications of M2M have already started to emerge in various sectors such as healthcare, vehicular, smart home technologies, and so on. The evolution of M2M has also begun in developing a smart power grid framework, referred to as the Smart Grid (SG). An electric grid having smart capability allows the power providers, distributors, and consumers to maintain a near real-time awareness of one another's operating requirements and capabilities. Through this awareness, SG is able to produce, distribute, and consume power in the most efficient and intelligent way. This type of communication takes place only amongst machines such as sensors, smart meters, and other equipments. Indeed, the M2M communication in SG requires to be private and secure since many of the autonomic functions that will run over it will be critical. SG will have numerous electrical appliances connected with one another in a complex manner so that they can report back on elements such as power consumption and other monitoring signals. This promises higher efficiency in the power distribution networks (i.e., greater availability of power to homes and factories at lower cost), and will allow distributed power generation such as local solar and wind generators. It will reach into home-based devices, which is why scalability and fast communication is crucial for practical deployment of SG.

To facilitate effective SG communication, existing networking technologies must be taken into account to deal with the multiple services and quality requirements of the residential appliances. The need to differentiate high- and low-priority traffic will be just as important as to be able to dynamically adapt the network to varying capacity requirements in real time. Therefore, it is essential that we consider appropriate technologies to implement the communication networks of SG, which may allow the flexible use of existing capacities without impacting the service quality of the SG.

Today's network infrastructure, largely based on Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) technologies, cannot physically or economically support the ever-changing demands caused by the overwhelming increase in bandwidth, transport of IP traffic, and the need for more flexible connectivity, higher resiliency, and network automation. To address this concern and to remain competitive, service providers have been investing heavily in building next-generation networks. Indeed, it is important to review how existing communication technologies such as IEEE 802.11 (WiFi), IEEE 802.15.4 (ZigBee), Bluetooth, and so on respond to the bandwidth and delay requirements of the M2M communication of SG. In this article, we provide a detailed M2M communication model for SG and verify the effectiveness of different adopted communication technologies. This article describes the shortcomings of the conventional networking technologies, which may be adopted for SG M2M communications. We also investigate on incorporating a level of intelligence in the smart meters so that we may be able to deal with such shortcomings and to improve the SG communications.

The remainder of this article is organized as follows. In Section II, we provide relevant research work. Section III describes our considered M2M communication model for SG. Section IV describes SG communication requirements and

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compares some existing communication technologies to find the most reliable one for the SG M2M communication. In Section V, we highlight the limitation of the conventional communication technique and provide directions towards implementing intelligent smart meters to deal with this problem. Finally, Section VI concludes the article with some future directions.

II. Related Research Work

Three task forces have been created for IEEE P2030 SG standards. These three task forces are dedicated toward standardiztation of power engineering, information, and communications technologies, respectively [1]. The policies laid out by the communication technology work group are broad in nature and should be considered as design directives for choosing suitable communication protocol in the SG M2M communications.

Recently, the Verizon Wireless and Qualcomm joint venture has focused on smart services enabled by M2M capabilities. This project envisions SG technology enabling utilities to wirelessly connect to their grid assets such as circuit breakers, transformers, and other substation equipments, allowing them to develop more interactive utility networks. Analysts predict that the M2M market will have more than 85 million connections globally by 2012 [2].

The work in [3] explored M2M communication applications and scenarios, which are growing and leading the way to new business cases. The work revealed the practical requirements and threats of M2M application scenarios and point out two main aspects, namely the unpredictable connectivity to the core network and the demand for high configurability and flexibility of M2M devices. While this work attempted to identify security threats against M2M communications, the exact technologies upon which M2M communications are based were not taken into account.

Ullo *et al.* [4] analyzed the main performances of IEEE 802.15.4 based Wireless Sensor Networks (WSNs) in order to evaluate their applicability in supporting the functionalities of SG. Their research showed that the WSN-based communication services exhibit reliable network services and may be of particular use in several SG applications. However, they did not investigate the exact SG applications that may be benefited from the deployment of such WSNs in the SG home area/automation networks. On the other hand, various challenges in the design of the home M2M network are presented in [5]. This work shows that the home networks are expected to require effective M2M gateways to facilitate communication among the various M2M devices and to provide a connection to a backhaul (e.g., with the core communication network of SG). While the backhaul connection may be fiber, cable, DSL, ethernet, or even cellular, the authors suggest that it is also important to choose appropriate network protocols to enable M2M devices to communicate inside a home environment. Among the available technologies to serve as the embodiment of the home area network, this work investigates IEEE 802.15.4 (ZigBee/6LoWPAN), IEEE 802.11 (WiFi), and Bluetooth protocols. However, that work did not take into account the impact of choosing these technologies in the specific case of SG M2M communications in the home area network. We focus our article on investigating the appropriate M2M communication technology suited for the residential networks belonging to a typical SG.

III. Considered Architecture for SG Communications

Fig. 1 shows our considered SG communication architecture. In this considered architecture, the SG power transmission and distribution system is separated from the communication system. For the sake of clarity, let us first briefly describe the power Distribution Network (DN). Power is delivered from the power plant to end-users through two components, namely the Transmission Substation (TS) located near the power plant and a number of Distribution Substations (DSs). TS delivers power from the power plant over high voltage transmission lines (generally over 230 kilo volts) to DSs. DSs, on the other hand, are placed in different regions and they are responsible for converting the electric power into medium voltage levels. DSs then distribute this medium-voltage level power to the building-feeders. To make it usable by the consumers, the building feeders have to convert the medium voltage level into a lower level.

For communication, however, the above consideration may not be applicable since the communication links have different requirements than those of the power lines. The TS and the Control Centers (CCs) of the DSs are connected with one another in a meshed network, which can be built over optical fiber technology. Next, the rest of the considered SG communication topology is divided into a number of networks that feature real-life set-ups of a city or a metropolitan area. Broadly speaking, a city has many neighborhoods, each neighborhood has many buildings, and each building may have a number of apartments. We derive our SG communication architecture from this real-life planning of a metropolitan area as described next.

The communication architecture for the lower distribution network (i.e., from CCs onward) is divided into a number of hierarchical networks, namely Neighborhood Area Network (NAN), Building Area Network (BAN), and Home Area Network (HAN). For simplicity, each DS is considered to cover only one neighborhood zone. Each NAN can be considered to be composed of a number of BANs. On the other hand, every BAN contains a number of apartments. In Fig. 1, the apartments are shown to have their respective local area networks, each of which is referred to as a HAN. In addition, there are advanced meters called smart meters deployed in the SG architecture that represent AMI for enabling an automated, two-way communication between the utility meter and the utility provider. The smart meters are equipped with two interfaces: (i) power reading interface and (ii) communication gateway interface. The smart meters used in NAN, BAN, and HAN are referred to as NAN GW (GateWay), BAN GW, and HAN GW, respectively. In addition, it is also worth mentioning that based upon the existing standards of SG, IP-based communications networking is preferred which permits

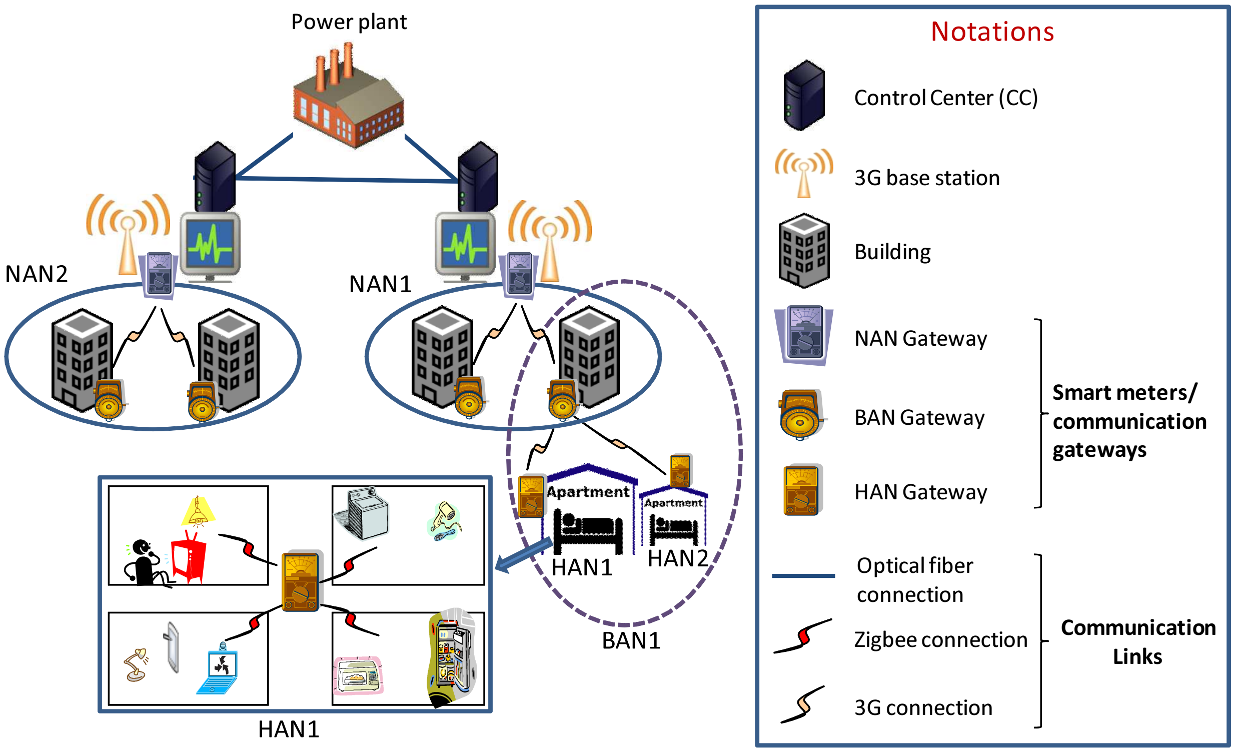

Fig. 1. Considered SG communications architecture.

virtually effortless inter-connections with HANs, BANs and NANs. Below, we describe the SG communication networks.

A. Neighborhood Area Network – NAN

A NAN is a localized or regional network of the considered SG communication topology. A NAN comprises one or more 3G base stations and a number of BANs. It is worth noting that the 3G framework used for SG communications should be separated from the existing ones used for providing other services, e.g., Internet. This should be done in order to prevent network congestion. Also, by this way, it is possible to avoid security threats arising from the Internet that may have impact on the delay-sensitive SG communications. It should be noted also that other modes of communications apart from 3G may also be alternative solutions for this purpose. The NAN GW can monitor how much power is being distributed to a particular neighborhood by the corresponding CC at the DS.

B. Building Area Network – BAN

Every building connected to the smart power grid maintains its own BAN. A BAN consists of a number of apartments having HANs. The BAN smart meter/GW is typically set up at the building's power feeder. The BAN GW can be used to monitor the power need and usage of the residents of the corresponding building. In order to facilitate BAN-HANs communication, 3G may be used to cover more areas.

C. Home Area Network – HAN

A HAN is a subsystem within the SG dedicated to effectively manage the on-demand power requirements of the end-users. For example, $HAN1$ in Fig. 1 connects the equipments (e.g., television, washing machine, oven, and so forth) in the end-user's apartment to a HAN GW, which, in turn, communicates with $BAN1$. Indeed, the HAN GWs are the ones that facilitate M2M communications in the SG framework. In other words, the HAN GW of a residence communicates with the electrical applicances of that residence that features as M2M communication. In the next section, we investigate the existing SG M2M network protocols and compare their performances.

IV. Towards Effective SG Communication

In the beginning of this section, we investigate the communication requirements for SG. Then, we survey a number of available network technologies that can facilitate M2M communication by fulfilling these requirements. We then present the best possible technology to be adopted for SG M2M communication, and also propose a simple enhancement to the existing technology to increase the effectiveness of the communication system.

A. SG communication requirements

SG communication depends on two important requirements [6], namely (i) communication latency and (ii) large volume of messages. If the CC misses any input from a HAN GW, this may affect the decision taken by the CC that may be important. If congestion occurs at the BAN GW, the packet may be delayed to be sent to the NAN GW and CC. Furthermore, it may also be dropped if the memory of the HAN GW becomes full due to (i) multiple messages arriving from different M2M devices at the same time and (ii) limited processing capability of the HAN GWs. If this is the case, the HAN GW may request the M2M device to retransmit the required packets. This also contributes to increased communication latency. While the overall SG communication latency in the order of a few miliseconds as depicted in the work in [6], [7] may not be practically achievable in large scale SGs, focus should be given towards reducing the communication latency as much as possible starting from the HAN level.

Hauser *et al.* [6] also suggests that the SG communication network should be able to accommodate more messages simultaneously without any major impact on communication latency. The large volume of messages in SG communication will affect the bandwidth required. Therefore, it is important to take into account if it is possible to reduce the number of messages received from many M2M devices at each HAN GW so that the total number of messages generated in the whole building does not overwhelm the BAN GW.

B. M2M Network Technologies for HAN

To meet the above requirements of SG communications, several short and medium range wireless technologies emerged in the recent past. The electric appliances found in a HAN represent the M2M devices. In order to choose an appropriate M2M network protocol in SG HAN, we need to take into account the features of M2M devices in terms of low power consumption. A number of low power and low cost technologies have evolved to present themselves as enablers of SG M2M communications. Among these, the prominent technologies include Bluetooth, IEEE 802.11 (WiFi), Ultra Wide Band (UWB), IEEE 802.15.4 ZigBee, 6LoWPAN, and so on. The major network technologies which can be adopted for HAN communications are presented below.

1) IEEE 802.15.3a – Ultra-Wide Band (UWB): UWB communications evolved for a number of applications that belong to two major types. The first type of application is for high data rate communications (typically over 1 Mbit/s) such as high definition television transmission. The other type of applications with data rate below 1 Mbit/s (e.g., sensor networks) can also employ UWB technology for communications. The M2M devices in a HAN that can be considered as sensors may use UWB technology. However, the shortcoming of this technology comprises in its high power requirements. Also, after several years of deadlock, the IEEE 802.15.3a task group was dissolved in 2006. Therefore, further support for UWB may not be possible in future if UWB is selected as the communication technology in the SG HAN.

2) IEEE 802.11 – WiFi: The IEEE 802.11 protocol, commonly referred to as WiFi, is suited for higher data rate applications over larger areas. WiFi is, by far, the most accepted protocol for wireless in-home communications. WiFi enjoys an enormous infrastructure for residences and have support for IPv6 addressing. The main shortcoming of this technology is similar to that of UWB, i.e., the high power requirement of the devices using WiFi. As a consequence, WiFi is considered not to be practical for the SG M2M communications.

3) IEEE 802.15.1 – Bluetooth: The Bluetooth protocol has become popular for wireless connections for voice, data, and audio applications over short range. The Bluetooth protocol stack supports IP addressing and therefore, can be adopted in SG HAN communication. The Bluetooth protocol suits well for low power/low data rate applications. However, Bluetooth works well in peer-to-peer communications over a short distance. Furthermore, Bluetooth networks or "piconets" support up to only 8 devices communicating simultaneously. To provide scalability amongst the M2M devices using Bluetooth, a HAN, therefore, will require to have a number of piconets (each consisting of 8 M2M devices). Each piconet has a master M2M device and the piconets are able to communicate with one another via their master devices. This, however, leads to increased communication latency. Another shortcoming of the Bluetooth technology consists in its periodical wake up and synchronization with the master device of the piconet. A Bluetooth device may consume approximately 3 seconds to wake up prior to synchronization.

4) IEEE 802.15.4 – ZigBee: IEEE 802.15.4 ZigBee is a protocol, which is employed in many home networking solutions including HANs. ZigBee was developed particularly for wireless devices ensuring low power and long life time. The ZigBee network layer allows for a cluster tree, self-healing mesh network, or star topologies, whereby the HAN GW and the M2M devices can be flexibly configured. Furthermore, ZigBee devices may take only milliseconds to exit their sleep states compared to bluetooth or WiFi devices. In addition, a ZigBee device using the Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) protocol does not require to schedule special wake up events in order to communicate and maintain synchronization with the HAN GW. Thus, the ZigBee technology presents itself as a much better candidate (for SG M2M communication in the home area network) than the UWB, WiFi, and Bluetooth technologies.

In Fig. 2 [8], the power consumption for each of the aforementioned protocols to be adopted for communication in SG home area network is shown. As it is evident from this graph, the Bluetooth and ZigBee protocols consume less power (both for transmission and reception) as compared with WiFi and UWB technologies. Furthermore, from our earlier explanation, ZigBee is a superior technology for HAN communication comparing with Bluetooth. Therefore, we adopt Smart Energy Profile (SEP) Version 1.5 as the communication protocol in HANs that employ ZigBee radio communications. We choose IEEE 802.15.4 ZigBee instead of other wireless solutions due to its low power requirements, and simple network configuration and management. Indeed, ZigBee provides a decent communication range of 10 to 100 meters while maintaining significantly low power requirement (1 to 100 mW) and thereby, lower cost.

V. Envisioned Improvement to HAN Communications based on ZigBee

As the HAN technology matures, the HAN GW should be able to intelligently manage the power concerns of the entire home network. In a conventional HAN, if the M2M devices always attempt to send their periodic messages to the HAN GW, the HAN GW is expected to receive a relatively high number of messages. Given the limited processing capability and low

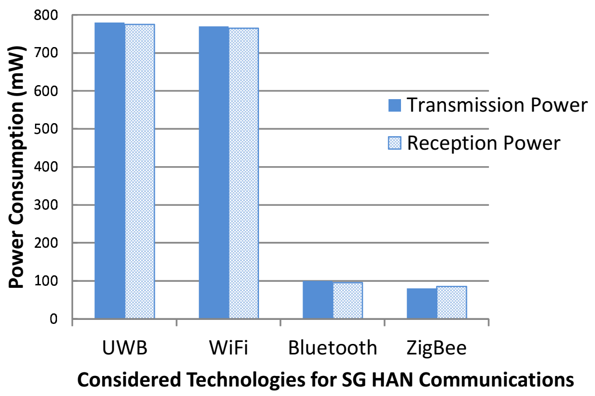

Fig. 2. Comparison of power consumption in case of different existing communication technologies adopted in SG home area network.

memory of the HAN GW, it is better if the M2M devices are designed to transmit their power requirements in a more efficient manner. Towards this end, we propose a simple yet effective solution. Let us assume that an M2M device, denoted by M_i transmits its power requirement messages to its HAN GW every δ time interval according to the conventional way. Now, let us assume that the power requirements of M_i remain the same in δ_t and δ_{t+1}. In this situation, we propose that M_i does not require to transmit its power requirement message to the HAN GW at δ_{t+1}. In other words, M_i remains in a silent mode unless its power requirement changes. Meanwhile, as the HAN GW is not receiving any periodic request from M_i, it initiates a substantially long timer T_i, within which the HAN GW assumes M_i to be in silent mode. During T_i, the HAN GW will expect the same power requirement from M_i. Upon expiration of the timer T_i, the HAN GW will send a beacon to M_i to be notified about its power requirements. Indeed, we expect that all the M2M devices in a HAN are not to change their power requirements frequently and/or abruptly. Thus, by incorporating this type of granular level intelligence about the status of the M2M devices, the HAN GW is not overwhelmed much by the incoming requests from many M2M devices at the same time.

Here, we illustrate how our envisioned approach improves the performance of the ZigBee protocol dedicated for SG HAN through a simple scenario. In this scenario, a ZigBee network is considered for the sake of comparison between our approach using silent mode and the conventional approach. We consider 100 electrical appliances in a residence that are connected with a smart meter acting as the HAN GW over ZigBee technology. The packet delivery ratio in the HAN GW is considered as a performance metric. We consider the simulation environment described in [9] whereby the link Bit Error Rate (BER) is varied from 10^{-6} to 10^{-5} and the statistical Packet Error Rate (PER) is assumed to be 0.2%. Each M2M device is considered to have a transmission range of 9 meters. The ZigBee operates in the 2.4 GHz ISM band at a rate of 250 Kbps. We also consider that the devices have the same power requirements during an average time period of one second. Each M2M device is assumed to send periodic messages following a Poisson distribution. The message transmission rate and the packet size are set to 10 packets/second and 90 bytes, respectively. As shown in Fig. 3, by varying the number of active appliances at the residence from 10 to 100, the proposed intelligent approach achieves much better packet delivery ratio even with the increase in the number of devices inside the HAN. On the other hand, the packet delivery ratio in the conventional approach decreases quickly as more active devices are included in the system. For instance, when all the 100 M2M devices are active, the packet delivery ratio for the intelligent system is 88% while in the conventional one, its value is approximately 55%. Fig. 3 indicates that the incorporation of intelligence using the proposed technique improves the performance of the ZigBee-based communication in the SG HAN.

VI. Conclusion

While we expect the smart power grids to continue to evolve in the next decade, it is necessary to consider the most robust and reliable technology to facilitate M2M communication in the home area networks. In this article, we highlighted the infrastructure of a smart grid and described the major technologies available today for enabling the smart grid home area communication. We emphasized on choosing ZigBee protocol for the enabler of M2M communication in smart grid environments as it performs far better than other communication technologies such as UWB, WiFi, and Bluetooth. It should be emphasized, however, that the described M2M communication in the smart grid takes place within the considered home area network, and that the communications between the other entities (i.e., between home and building area networks, and between building and neighborhood area networks) are for data forwarding only. In other words, M2M communication is not occurring in the later entities in the presented SG model. In addition, we presented a technique to improve the performance of the conventional ZigBee-based M2M communications in SG by incorporating intelligence in the smart meter and the M2M devices of the HAN. In future,

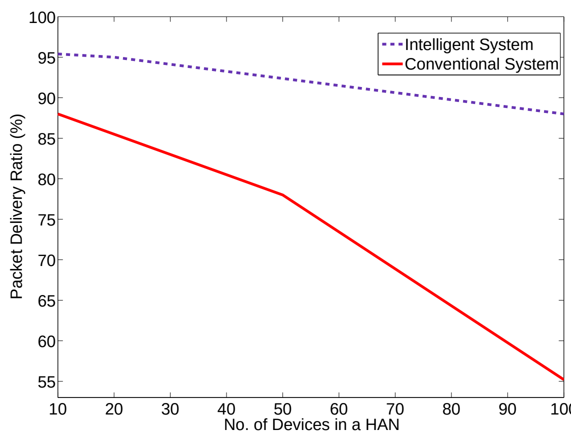

Fig. 3. Comparison of packet delivery ratio for the conventional and the improved (i.e., intelligent) systems based on ZigBee.

the issue of the coexistence of different M2M communication technologies may require adequate attention.

REFERENCES

[1] Available at, "IEEE, conference drive smart grids", http://www.eetimes.com/electronics-news/4081867/IEEE-conference-drive-smart-grids
[2] Available at, http://smartgrid.testing-blog.com/tag/m2m/
[3] I. Cha, Y. Shah, and A. U. Schmidt, "Trust in M2M Communication", IEEE Vehicular Tech. Mag., vol. 4, no. 3, Sep. 2009, pp. 69-75.
[4] S. L. Ullo, A. Vaccaro, and G. Velotto, "Performance Analysis of IEEE 802.15.4 based Sensor Networks for Smart Grids Communications", Journal of Electrical Engineering: Theory and Application, Vol. 1, No. 3, Apr. 2010, pp. 129-134.
[5] M. Starsinic, "System Architecture Challenges in the Home M2M Network", in Proc. Applications and Tech. Conf., Long Island, USA, May 2010.
[6] C. H. Hauser, D. E. Bakken, I. Dionysiou, K. H. Gjermundrod, V. S. Irava, J. Halkey, and A. Bose, "Security, Trust, and QoS in Next Generation Control and Communication for Large Power Systems", Int. J. Critical Infrastructures (IJCIS), vol. 4, nos. 1/2, 2008, pp. 3-16.
[7] R. Vaswani and E. Dresselhuys, "Implementing the Right Network for the Smart Grid: Critical Infrastructure Determines Long-Term Strategy", White Paper, available at, http://www.silverspringnet.com/pdfs/
[8] J-S. Lee, Y. Su, and C-C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi", in Proc. 33^{rd} Annual Conf. of the IEEE Industrial Electronics Society (IECON), Taipei, Taiwan, Nov. 2007.
[9] J. Zheng and M. J. Lee, "A comprehensive performance study of IEEE 802.15.4", Sensor Network Operations, IEEE Press, Wiley Interscience, Chapter 4, 2006, pp. 218-237.

BIOGRAPHIES

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